ON ANOMALOUS DARK PATCHES IN SATELLITE-VIEWED SUNGLINT AREAS

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ABSTRACT

Irregularities in sea-surface sunglint patterns have been frequently noticed in photographs from earth-orbiting satellites. High-resolution color photographs from low-altitude manned spacecraft missions have shown small-scale detail in many of the sunglint pictures. At the much higher altitude of the Applications Technology Satellites (ATS) the reflection pattern of the sun is spread over such a large area that varying sea-surface conditions can be inferred in many areas within a single sunglint region.

Of particular interest are patches or swaths of ocean surface that appear dark within the brighter sunglint region. Short-period time sequences of photographs from ATS III exhibit reversals in brightness when the horizontal specular point moves into the area of the anomalous dark feature.

Modeling statistics of sea-surface slope for increasing near-surface wind velocities show 1) a rapid drop in maximum sunglint radiance and 2) an increase in the area covered by the total glint pattern. It is shown, by combining calm surface conditions with higher background sea states, that sunglint patterns can be obtained which are very similar to those observed from satellites. Consequently, anomalous dark swath observations from ESSA satellites can be used to infer sea-state variations. The streaklike anomalies in many cases correspond to calm waters beneath high-pressure ridges or, when paralleling coastlines, the seaward limit of local sea-breeze circulations.

1. INTRODUCTION

With the increasing number of high-altitude photographs of the earth's surface have come increased observations of the sun's reflection, or glint, from the ocean surface. Several researchers have studied the sunglint phenomenon. Cox and Munk (1954, 1956) conducted and reported on an extensive field study that resulted in a correlation of sea-surface slopes with glint. Since the air-sea temperature difference was negligible, they further correlated the glint with the wind at 13 m. Rozenberg and Mullamaa (1965) have continued the Cox and Munk work a step further by investigating the asymmetry alterations of the glint under varying wind directions. Duntley and Edgerton (1966) discussed glint observations from satellite photographs. From the above references, two basic results emerge for a fixed optical system: 1) the reflectance at the specular point decreases with increasing sea state and 2) the width of the diffuse reflection region around the specular point increases with increasing sea state. The sea state is a complex function of the atmosphere directly above the surface—the fetch of the wind, the duration of the wind, the past history of the wind, and the stability of the marine boundary layer are all involved. Occasionally it may be necessary to account for any molecular film present on the water surface, which will damp capillary wave generation by the turbulent atmosphere above.

It will be shown that a fairly simple treatment of the general results, already documented, explains the dark patches frequently noted in the sunglint region, especially when they are viewed from great altitudes.

2. MODELING OF AN ANOMALOUS DARK STREAK

By employing the empirical statistics of sea-surface slopes (Cox and Munk, 1956), a model has been devised that maps reflected sunglint at the satellite (Strong and Ruff, 1969). Using solar and satellite position, the glitter pattern can be reproduced for any wind (13 m above the surface) from 0 to 20 m sec^{-1}. A gnomonic projection presents the data in a form that can be directly compared with a digitized satellite photograph. As might be expected, the most dramatic difference in reflected brightness patterns occurs between smooth and roughened sea surfaces. The optical properties of a calm surface are easily distinguished from those of a rough surface. Figure 1 depicts the reflectivity pattern that would obtain for a band of calm water, approximately 100 mi wide, through a region where the ocean surface is roughened by a 5 m sec^{-1} wind. In this hypothetical situtation, the specular point (this point, or area, is defined where the horizontal, or zero slope, reflection occurs) falls within the smooth region; thus the dark band reverses to very bright in the vicinity of this point. Were the calm swath outside the central-most portion of the glint, it would appear dark along its entire length as shown in figure 2. Thus it is seen that both the brightest and darkest areas within the sunglint region correspond to the lightest winds and smoothest seas.

3. OBSERVED SUNGLINTS

ATS OBSERVATIONS

The Applications Technology Satellites (ATS) now provide earth-synchronous coverage from an altitude of 35,800 km over the Equator. Currently, ATS I and ATS III supply two such observation points over the Pacific and Atlantic Oceans. Pictures covering the whole disc of the earth can be generated and transmitted at 15- to 20-min intervals from sunrise to sunset. From daily sequences of pictures at this altitude, the sunglint is immediately apparent as it moves from east to west across the earth's tropical belt. The latitude of the observed
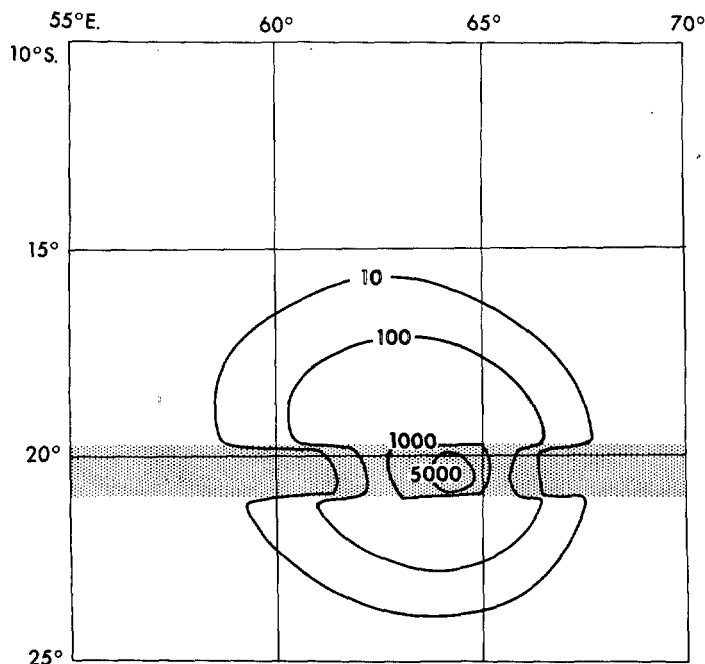
FIGURE 1.—Theoretical sea-surface sunglint for a composite pattern; 5 m sec $^{-1}$ wind background and a calm wind in an east-west swath (shaded) through the specular point. Isopleths are relative reflected intensity per 10^4 steradian incident flux; subsatellite point, 21.5° S., 65.5° E.; subsolar point, 5.8° S., 35.6° E.; satellite height, 722 km.

FIGURE 2.—Theoretical sea-surface sunglint for a composite pattern; 5 m sec $^{-1}$ wind background and a calm wind in an east-west swath near specular point (shaded). Other aspects are the same as those in figure 1.

specular point falls between the Equator (subsatellite point) and the subpolar point. For earth-orbiting satellites, the angle subtended by the earth at the satellite decreases rapidly with increased distance from the earth. However, the angle subtended by the sun, or by the sun's reflected image on the sea surface, remains nearly constant. Therefore, the glint as viewed from a geostationary altitude, which is much greater than that of most polar-orbiting satellites (namely, 1500 km or lower), covers considerably more ocean area.

Pictures from ATS III frequently exhibit anamolous dark patches or streaks within the diffuse sunglint area. One such pronounced irregularity is illustrated by the sequence for Mar. 12, 1968, shown in figure 3. Prior to the specular point entering the Pacific Ocean (fig. 3A), a large area off Ecuador at the Equator appears dark within the surrounding diffuse solar reflection. Clusters of convective clouds are seen irregularly distributed over the ocean between the South American mainland and the Galapagos Islands (1.0° S., 91.0° W.). This scattered cloud cover occurs both within and outside the glint area. As the sunglint area progresses westward into the Pacific (fig. 3B), the dark patch changes in reflectivity to become extremely bright. The brightest return appears when the specular point coincides with the area of concern. Completing the sequence (fig. 3C), the patch reverts to dark again as the specular point advances westward.

A similar ATS III sequence for Mar. 19, 1968, is illustrated in figure 4. The region to be noted is to the north and west of the Galapagos Islands (see arrow). Note the
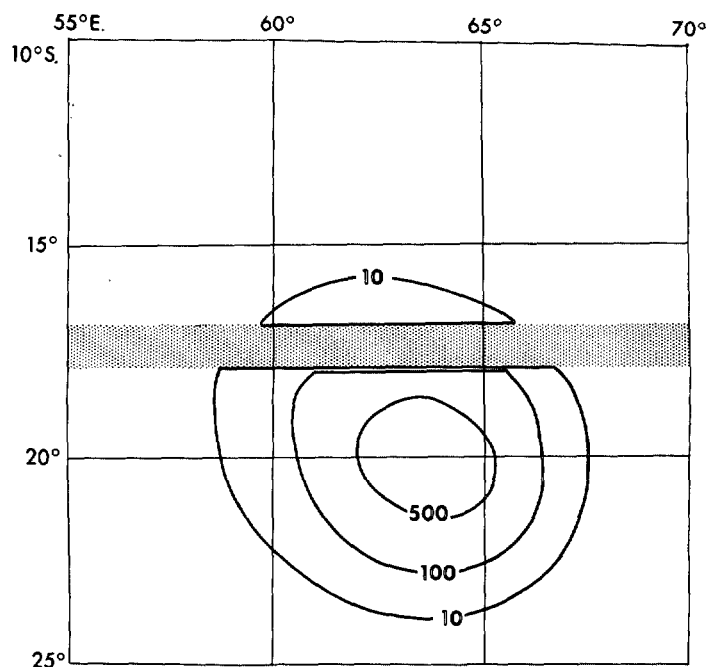
dark streak originating at the islands in figure 4A. The length of this streak is nearly 400 km. As the specular point moves to the anomalous dark streak (fig. 4B) and then past the position of the anamolous dark streak (fig. 4C), an intensity reversal to bright and back to dark takes place. In this example, the only clouds evident are in an arrangement that suggests alinement with the volcanic peaks on the islands. Surface-pressure charts for both these equatorial Pacific cases are presented in figures 5 and 6. On March 12 (fig. 5), the surface winds were light with scattered showers and thundershowers reported off the coast of Ecuador. On March 19 (fig. 6), typical southeasterly trades are found over the northwestward-flowing Peru (Humboldt) Current in the vicinity of the Galapagos Islands.

Although surface observations are nonexistent, the following condition is hypothesized as being responsible for the observed surface streak off the Galapagos Islands (a diagrammatic map is presented in fig. 7). With the preferred March air and water movement toward the northwest, the island group represents a disturbance in the wind's and current's path. At this time of year, the thermocline is nearly at the surface. Sufficient disturbance, either by the atmosphere or the islands, would mix the waters in the surface layer. Mixing, with the shallow thermocline, will lower the surface temperature considerably. Consequently, a cool streamer would be produced downstream from the islands.[1] If, in fact, this cooling does take place, the marine inversion would be intensified.

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[1] Although the time and location were not completely coincident, surface temperature observations from the research vessel *Thomas Washington* on March 17 did show cooler water northwest of the islands (22.8°C at 1.5° N., 92.5° W., contrasted to 26.7°C at 2° N., 95.0° W.).
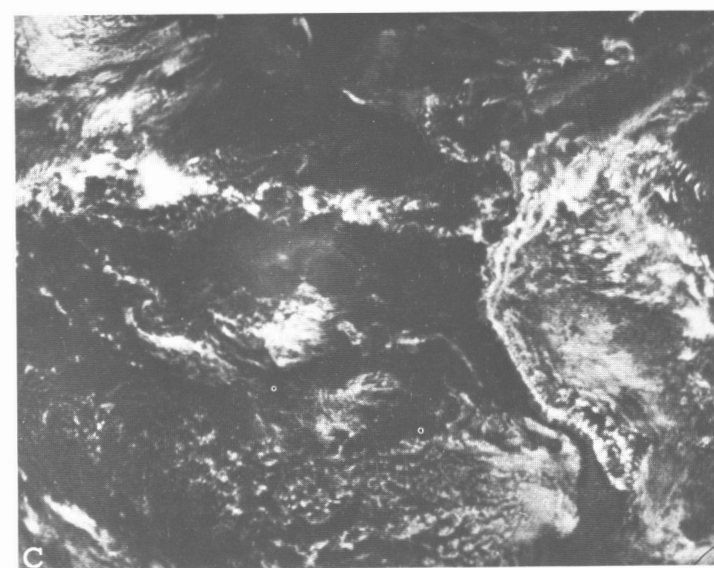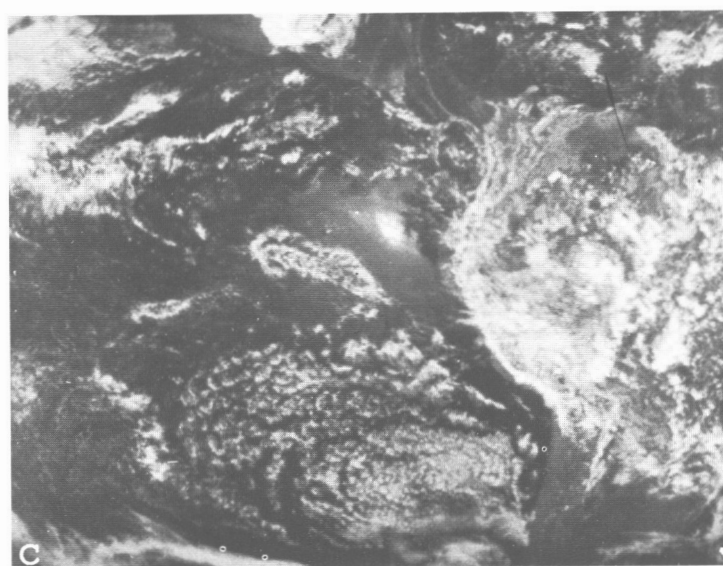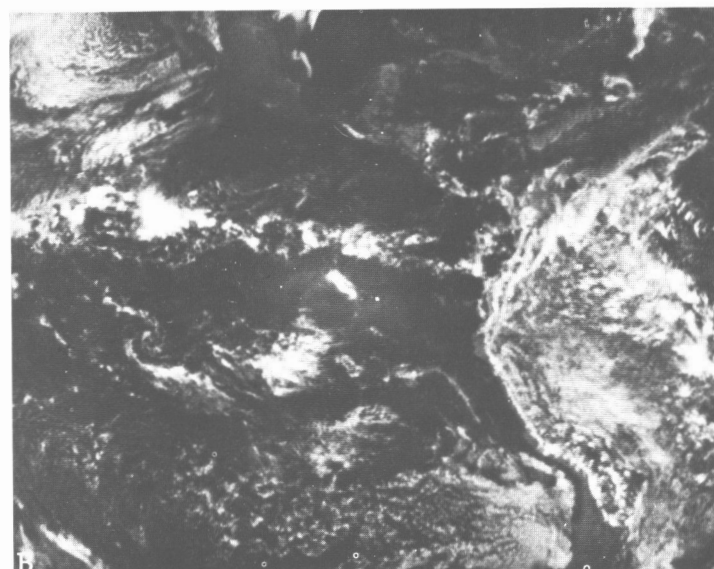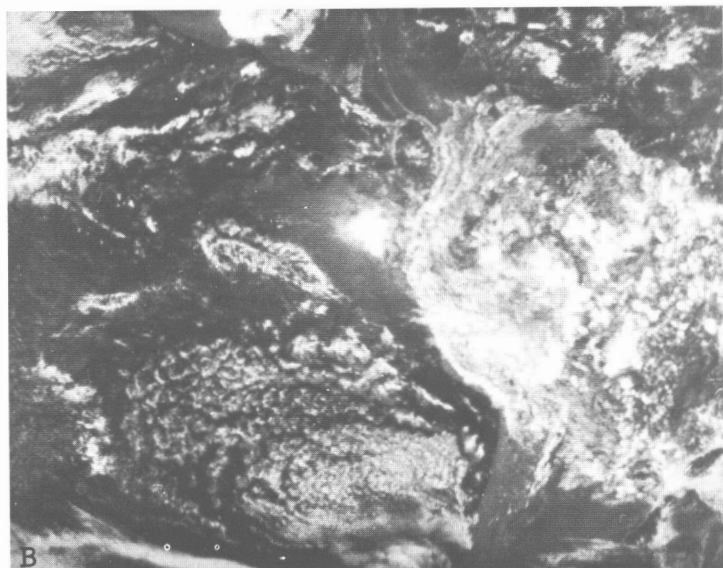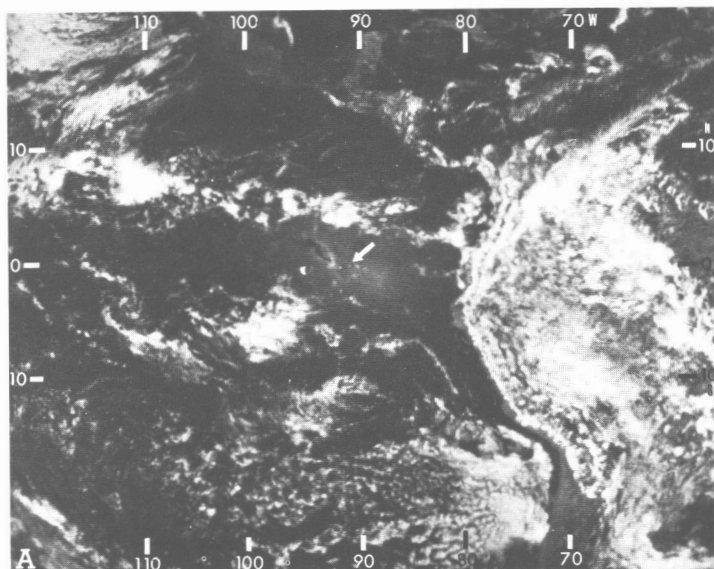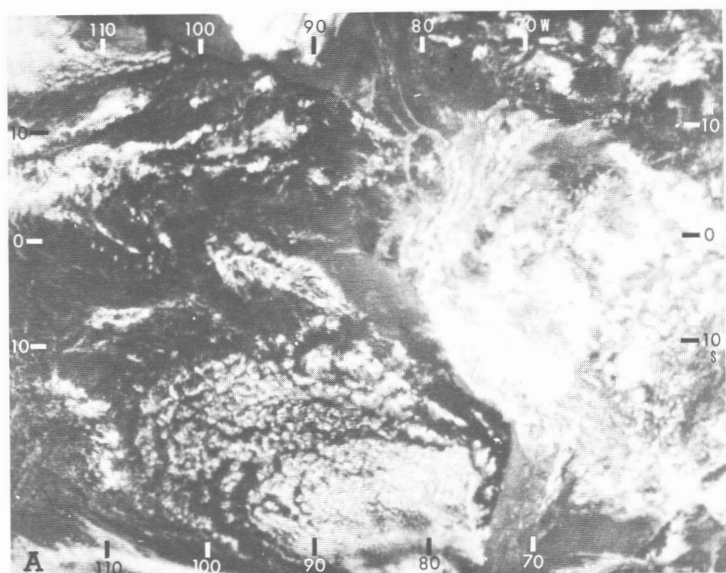
FIGURE 3.—ATS III image dissector camera photograph on Mar. 12, 1968; (A) 1658:31 GMT; (B) 1729:31 GMT; (C) 1800:24 GMT.

FIGURE 4.—ATS III image dissector camera photograph on Mar. 19, 1968; (A) 1826:24 GMT; (B) 1858:08 GMT; (C) 1930:35 GMT.
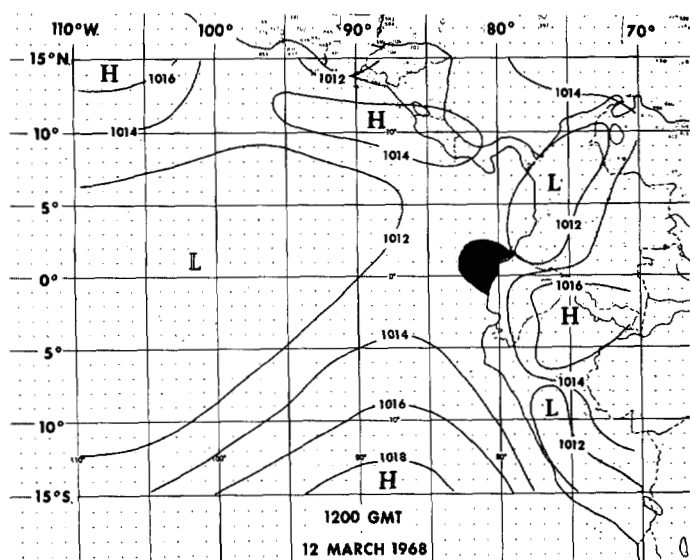
FIGURE 5.—Surface equatorial pressure analysis for the eastern Pacific at 1800 GMT on Mar. 12, 1968; shaded area depicts anomalous surface feature.
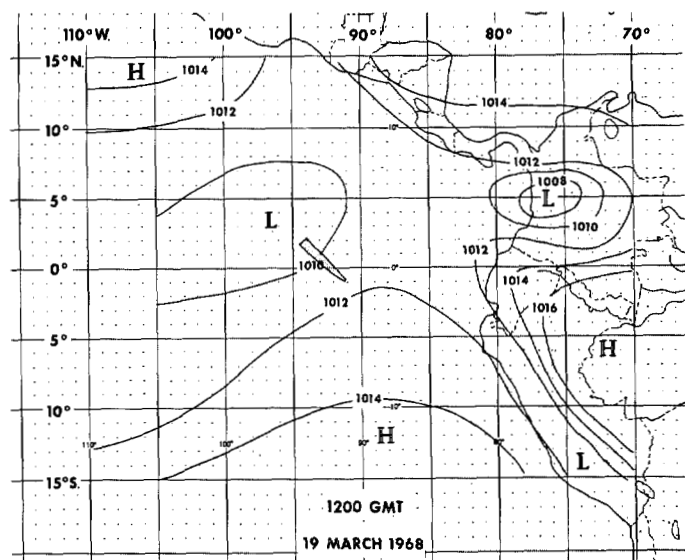

FIGURE 6.—Surface equatorial pressure analysis for the eastern Pacific at 1800 GMT on Mar. 19, 1968; shaded area depicts anomalous surface feature.

Any heat input to the air passing over the islands would further intensify the downwind inversion. Subsequently, momentum exchange between the atmosphere and the ocean northwest of the islands would be considerably inhibited. Therefore, a streak of calm water may be anticipated. The behavior of the reflection patterns agrees with the expected dark-bright reversal as shown by the model for a swath of calm water.

ESSA SATELLITE OBSERVATIONS

Sunglints frequently appear in the pictures obtained by the ESSA and Nimbus meteorological satellites, which are in sun-synchronous polar orbits at altitudes from 1100 to 1500 km. On nearly any day, one may expect to find at least one anomalous dark streak in conjunction with a sunglint. Many of the dark streaks are found in the central portions of oceanic anticyclones where winds typically are light and variable and cloudiness is at a minimum. The stability of the marine boundry layer is most critical in regard to air-sea interaction at these low wind speeds. Both laminar and turbulent flow regimes are possible, and these variabilities directly affect the character of the underlying sea surface (Strong, 1968). The vertical momentum transfer is drastically reduced under the near-laminar flow found in strong inversions.

Examples of ESSA or Nimbus satellite photographs of anomalous dark streaks have been given by Fujita (1963), National Council on Marine Resources and Engineering Development (1967), Parmenter (1969), and Anonymous (1964); but very limited explanations have been introduced with these photographic presentations. Two additional examples are provided in figure 8, and corresponding surface weather analyses are given in figure 9. These two types of sunglint patterns have been found to be typical of slightly different meteorological conditions. Figure 8A
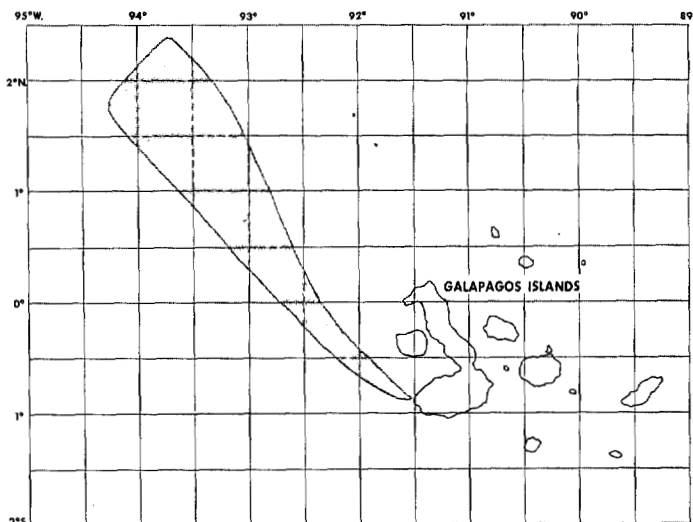

FIGURE 7.—Shaded area coincides with dark streak observed in figure 4.

shows a long swath of anomalous reflectivity in the North Pacific which coincides with an elongated high-pressure ridge locally complicated by the intrusion of a weak cold front. In figure 8B, the glint pattern appears mottled. This is characteristic of a broader high-pressure cell. High-pressure features not only have low wind speeds near their centers but are also characterized by subsidence, which tends to suppress cloudiness.

A survey of photographs from ESSA satellites over a 1-yr period yielded three oceanic areas displaying frequent sunglint anomalies: 1) the Arabian Sea, 2) the Bay of Bengal, and 3) the equatorial Pacific north and east of the Galapagos Islands. These areas are frequently under the influence of weak pressure gradients and cloud-free skies associated with anticyclonic conditions.
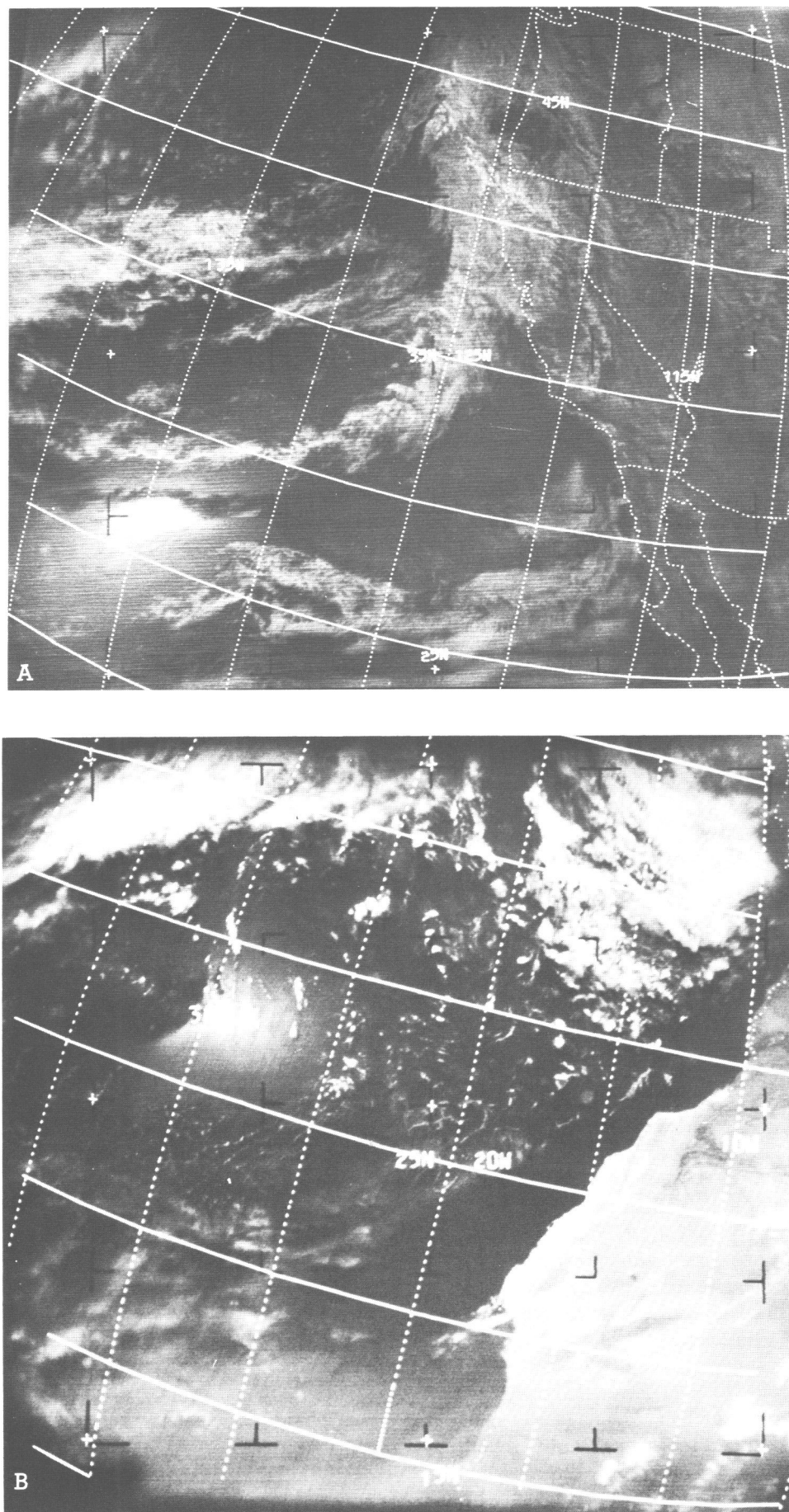
FIGURE 8.—Dark anomalies observed from ESSA satellites; (A) ESSA 7 at 2243:46 GMT on Nov. 4, 1968; (B) ESSA 5 at 1615:15 GMT on June 8, 1967.
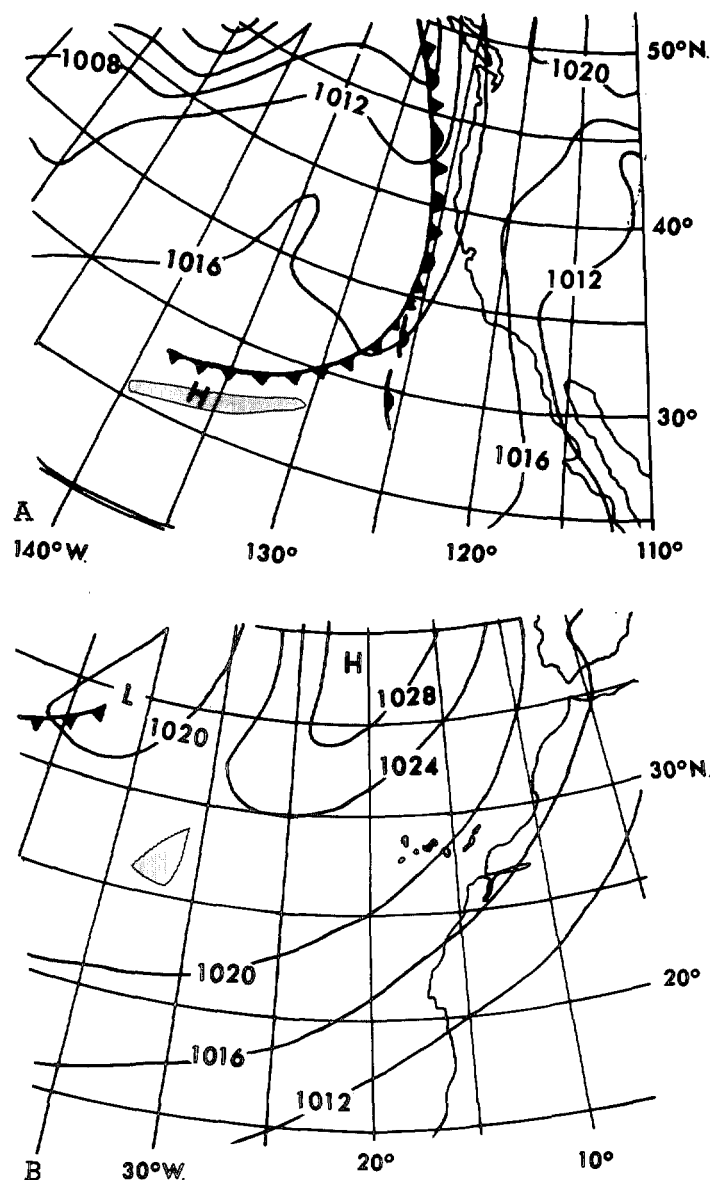
FIGURE 9.—Surface pressure analyses for figure 8; shaded area represents low sea state; (A) 0000 GMT on Nov. 5, 1968 and (B) 1200 GMT on June 8, 1967.

GEMINI AND APOLLO AND AIRCRAFT OBSERVATIONS

Manned spacecraft missions have provided high-resolution color photographs of the ocean. Some frames include sunglint with anomalous dark patches, similar to those previously discussed, appearing within the diffuse solar reflection. In a previously published Gemini 12 picture of a dark streak off the Florida Peninsula (Stevenson, 1968), calm water was hypothesized as the cause. This color picture is reproduced in black and white in figure 10 with the associated surface weather conditions found in figure 11. The dark streak roughly parallels the southwestern shore from Tampa to the Florida Keys. In the southern portion of the dark streak, the coincidence of the specular point causes the dark streak to revert locally to an extremely bright patch. Attention is also directed to the variable brightness pattern on Lake Okeechobee. The dark area off the western shore is due to a localized area of calm

water. Surface weather observations indicate that a sea breeze along the Gulf shore of Florida had interrupted the northeasterly winds prevailing over most of the remaining area. The low-level wind divergence at the western limit of the sea breeze undoubtedly produced a band of near-zero surface winds in approximately the same region as the observed dark streak on the surface. Such a divergent horizontal flow at the air-sea interface would induce upwelling, providing nutrient enrichment and the attraction of fish. Thus serendipity may play an important role in remote sensing.

Aerial photographs of sunglint areas from NASA's *Convair 990* aircraft show nearly parallel slicks on the sea surface. One such photograph is shown in figure 12. This single sunglint photograph provides an excellent example of how the reflection from slicks revert from very bright to very dark within a more diffuse reflection from the rougher surface. The reader is again referred to figure 1. The high resolution of the Gemini and Apollo pictures has enabled detection of these small-scale slick patterns here also. Figure 13 is a black and white reproduction of a color photograph from Apollo 7. Although these alternating sea states produce dark-bright reversals that are similar to those discussed earlier, they are too small to be observed from the higher orbiting ESSA, Nimbus, and ATS satellites. With these satellites the picture resolution is too coarse for the discrimination of slicks, which are of the order of a few tens of meters in width. From these satellites it is the rather extensive near-calm areas (that is, tens or hundreds of kilometers in length and width) that are associated with dark-bright reversals in sunglint regions.

4. CONCLUSIONS

A number of examples of anomalous dark streaks or patches within satellite-viewed sunglint areas have been presented. The dramatic reflected brightness shift observed as the specular point moves into these regions suggests an abrupt change in the character of the sea surface.

From the knowledge that, at low wind speeds, changes in the marine boundary layer structure are related to variations in momentum transfer at the air-sea interface, a model has been presented that explains this phenomenon. The reflection pattern from the calm sea state that exists beneath a calm atmosphere is optically quite different from that for the rippled surface that occurs in response to light winds. These optically contrasting areas will stand out as distinct dark patches or strips in the diffuse glint region or, if the specular point lies within the calm water, as anomalous bright patches within the general glint area.

An earlier hypothesis (Fujita, 1963), that extremely thin cirrus clouds are chiefly responsible for the anomalous dark streaks observed within glint areas, is discounted. This perhaps explains some dark patches, but the argument is untenable with respect to the dark-bright transitions that occur as the specular point moves across a region.
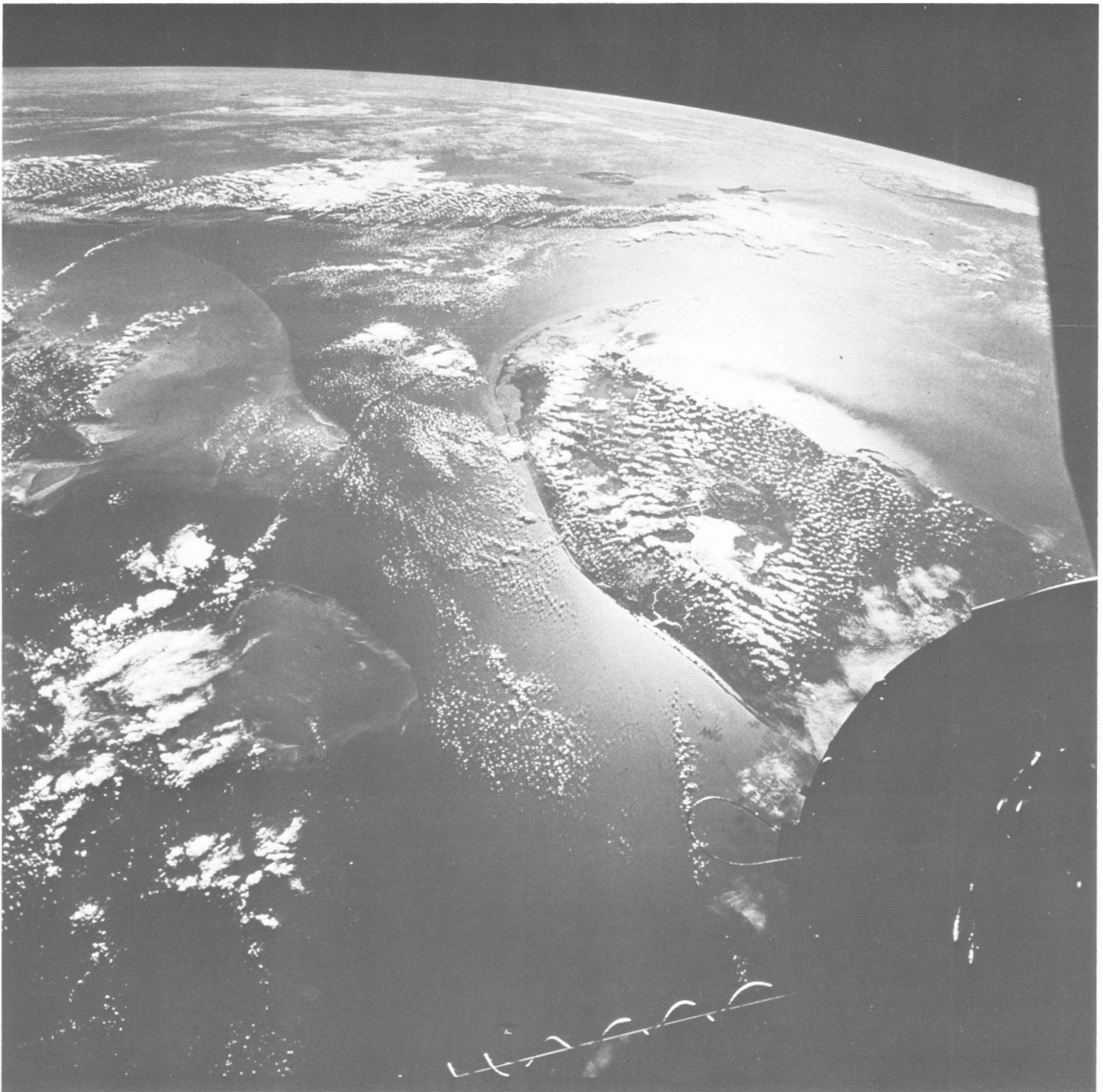
FIGURE 10.—Gemini 12 photograph (274-km altitude) looking southwest across the Florida Peninsula at 1913 GMT on Nov. 12, 1966; note dark streak about 30–40 km offshore.

The use of an earth-synchronous satellite provides not only continuous surveillance of the Tropics from sunrise to sunset but, of necessity, an altitude that results in the sunglint area being spread over an extensive region of the ocean. If cloudiness is not too restrictive, brightness irregularities at low sea states may be easily delineated by noting the anomalously dark and bright patches within the general glint region.

Frequently, this condition will result from a divergent wind field above the interface. Such conditions will induce upwelling to cool the surface water. Further inhibition of momentum transfer through the marine boundary layer will serve to damp wave generation. The location of such areas, which are generally nutrient rich, would aid the fishing communities of neighboring countries.
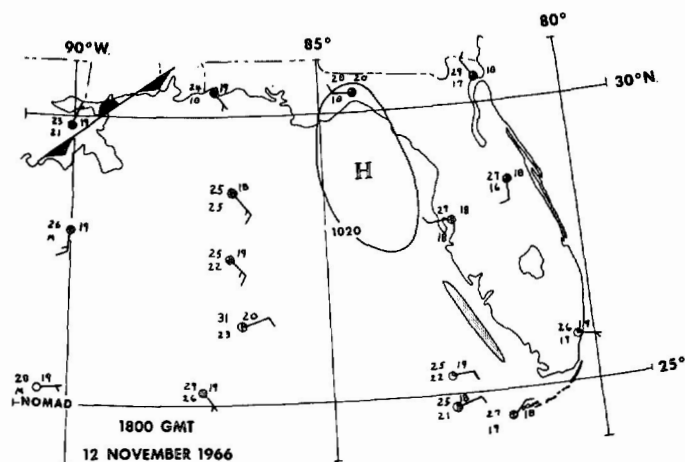
FIGURE 11.—Surface weather analysis for the eastern Gulf of Mexico at 1800 GMT on Nov. 12, 1966; shaded area represents low sea state.

Of all the sunglint patterns that have been observed from space, anomalously dark and bright areas should depict regions of calm seas where the surface wind stress approaches zero. Microwave instruments (Moore and Pierson, 1967) are being tested that hold promise of extending remote sea-state measurements to the larger waves and more hazardous moods of the restless sea. Further, microwave measurements are not nearly as limited by sun-satellite geometry and cloud cover as those in the visible spectrum.
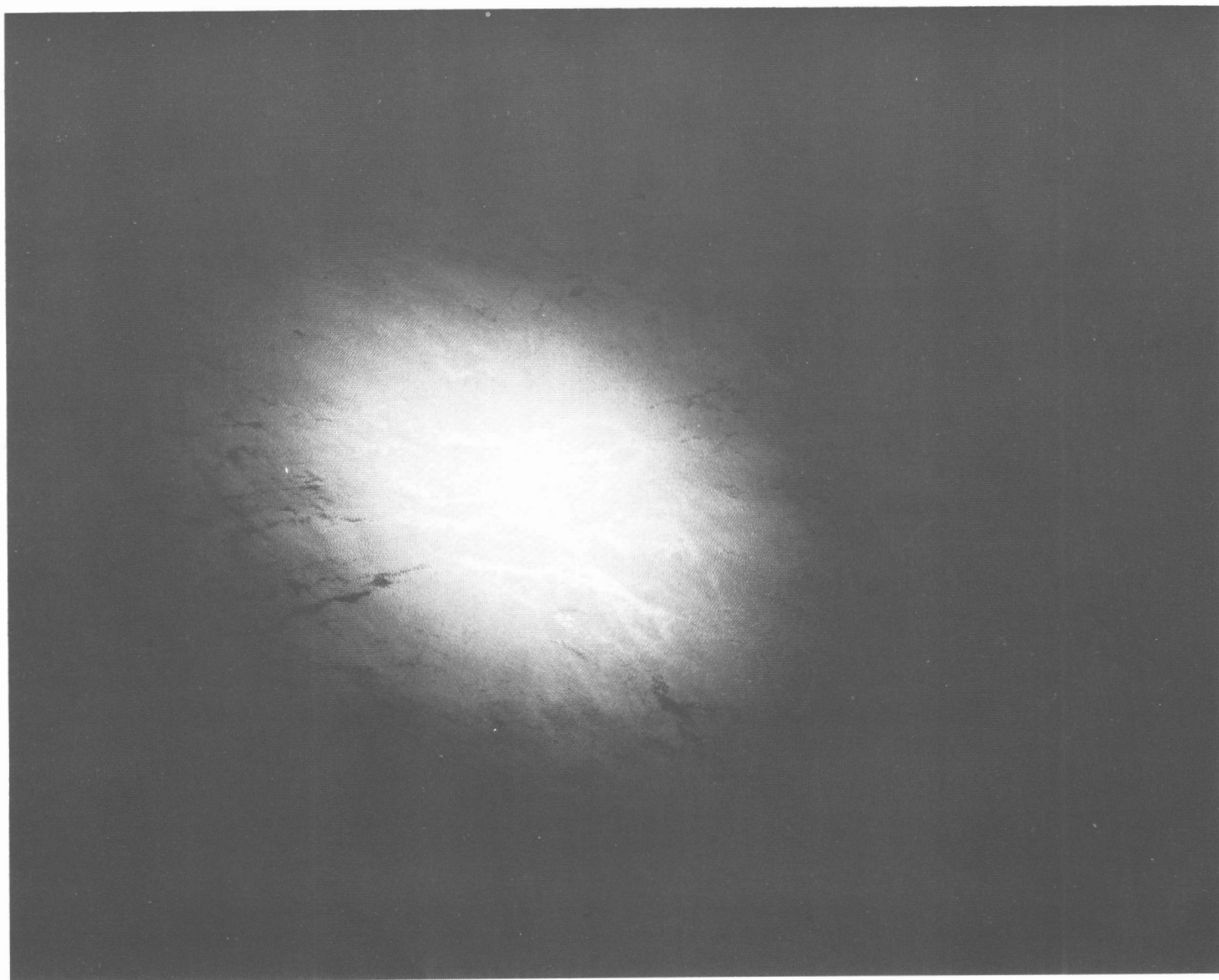
ACKNOWLEDGMENTS

FIGURE 12.—NASA *Convair 990* photograph (10-km altitude) of the southern Gulf of Mexico at 1838 GMT on June 5, 1967.
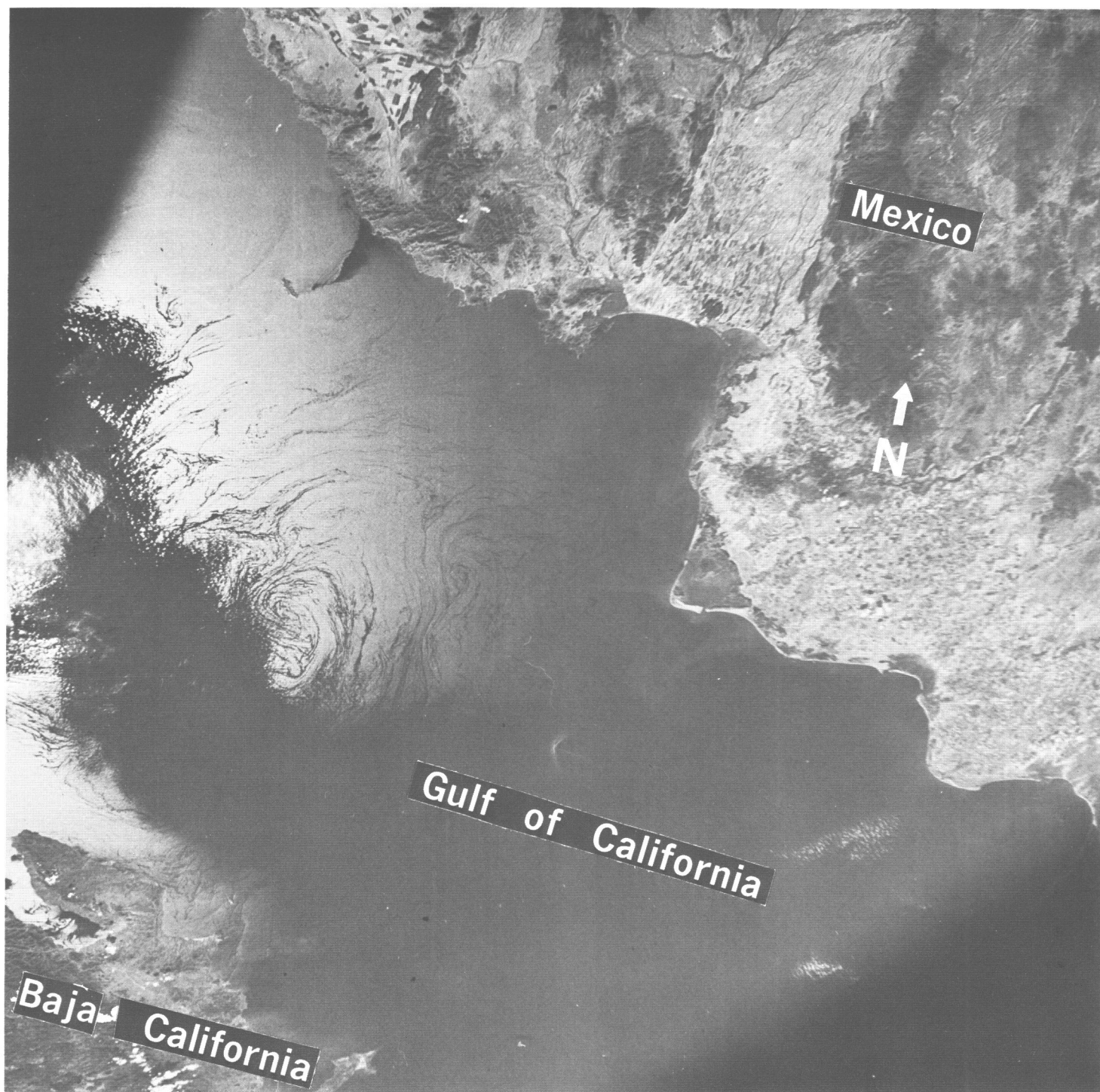
FIGURE 13.—Apollo 7 photograph (226-km altitude) of the Gulf of California at 1936 GMT on Oct. 13, 1968.

REFERENCES

Anonymous, "Picture of the Month," *Monthly Weather Review,* Vol. 92, No. 10, Oct. 1964, p. 474.

Cox, C., and Munk, W., "Measurement of the Roughness of the Sea Surface From Photographs of the Sun's Glitter," *Journal of the Optical Society of America,* Vol. 44, No. 11, Nov. 1954, pp. 838–850.

Cox, C., and Munk, W., "Slopes of the Sea Surface Deduced From Photographs of Sun Glitter, *"Bulletin of the Scripps Institution of Oceanography,* Vol. 6, No. 9, 1956, pp. 401–488.

Duntley, S. Q., and Edgerton, C. F., "The Use of Meteorological Satellite Photographs for the Measurement of Sea State," *Final Report* No. II–2, Contract No. NObs. 86012, U.S. Navy Bureau of Ships Project FAMOS, La Jolla, Calif., June 1966, 129 pp.

Fujita, T., "Use of TIROS Pictures for Studies of the Internal Structure of Tropical Storms," *Mesometeorology Project Research Paper* No. 25, Department of the Geophysical Sciences, University of Chicago, Oct. **1963**, 21 pp.

Moore, R. K., and Pierson, W. J., "Measuring Sea State and Estimating Surface Winds From a Polar Orbiting Satellite," *International Symposium on Electromagnetic Sensing From Space*, Polytechnic Press, Polytechnic Institute of Brooklyn, New York, **1967**, pp. R1–R28.

National Council on Marine Resources and Engineering Development, *United States Activities in Spacecraft Oceanography*, Washington, D.C., **1967**, 44 pp.

Parmenter, F. C., "Picture of the Month—'Sunglint,'" *Monthly Weather Review*, Vol. 97, No. 2, Feb. **1969**, pp. 155–156.

Rozenberg, G. V., and Mullamaa, Yu. A. R., "Some Possibilities of Determining Wind Speed Over an Ocean Surface Using Observations From Artificial Earth Satellites," *Atmospheric and Oceanic Physics Series*, Vol. 1, No. 3, Izvestiya of the Academy of Sciences, U.S.S.R., Apr. **1965**, pp. 282–290.

Stevenson, R. E., "Weltraum-Ozeanographie: der synoptische Anblick des Ozeans aus dem Weltraum," (World Oceanography: A Synoptic Look at the World Oceans), *Die Umschau*, Vol. 68, No. 21, Frankfurt, Oct. 10, **1968**, pp. 643–649.

Strong, A. E., "The Spring Lake Anticyclone: Its Inducement on the Atmospheric and Water Circulations," Ph. D. thesis, Department of Meteorology and Oceanography, University of Michigan, Ann Arbor, **1968**, 146 pp.

Strong, A. E., and Ruff, I. S., "A Model of Satellite-Observed Solar-Reflections From the Sea Surface," Environmental Sciences Group, National Environmental Satellite Center, ESSA, Hillcrest Heights, Md., **1969**, (submitted for publication in *Journal of Marine Research*).